Spacecraft Alignment Determination and Control for Dual Spacecraft Precision Formation Flying

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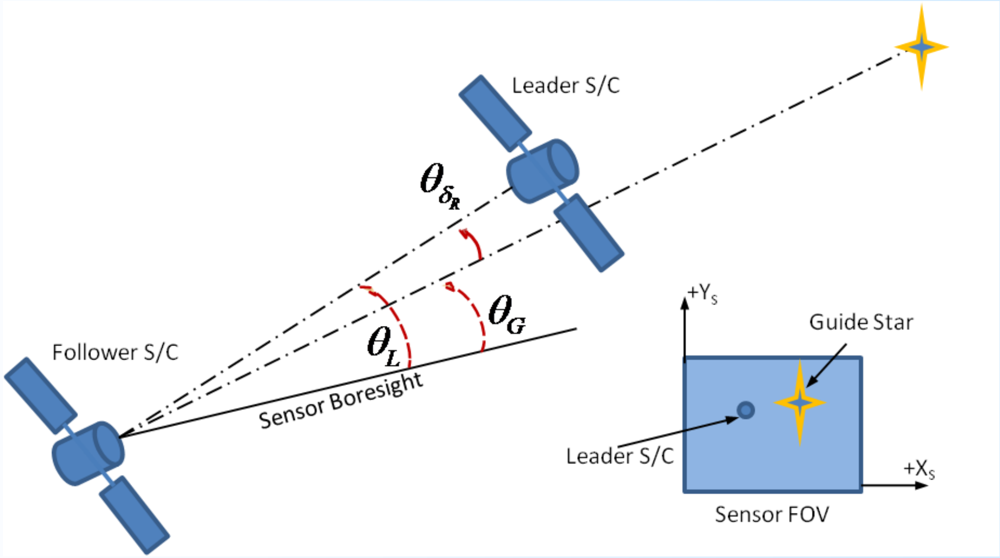
Overview

- VT Concept
  - Astrometric Alignment Concept for Virtual Telescopes (VT)
  - Proposed Missions (MASSIM, New Worlds Observer)
- Stability Requirements and Measurement Models
  - Attitude and Translation Stability Requirements
  - Optical Alignment and Ranging System Measurement Models
- Dynamics and Controls Framework for GN&C Design
  - Dynamics Model Formulation
  - Inertial Measurement Models (IRU, Accelerometers)
- Case Study: GN&C Design for a Heliophysics Mission
  - Navigation Modes for Fine Alignment Acquisition
  - GN&C Architecture Comparison
- Conclusions

VT Concept

- **Formation flying missions seek to advance science imaging by utilizing precision dual spacecraft formation flying. ("Virtual" Telescope (VT))**
  - **Milli-Arc-Second Structure Imager (MASSIM) (Astrophysics X-ray imaging) (Sep ~ 1000 km)**
  - **New Worlds Observer (NWO) (exoplanet mission) (Sep ~ 25,000 km)**
  - **Heliophysics concept missions for Solar Coronagraphs and Solar imaging (Sep. 50m – 500m)**



Dual Spacecraft Precision Astrometric Alignment Sensing Architecture

Objective: Develop models for a complete GN&C design framework of VT architectures

VT Attitude and Translation Stability Requirements

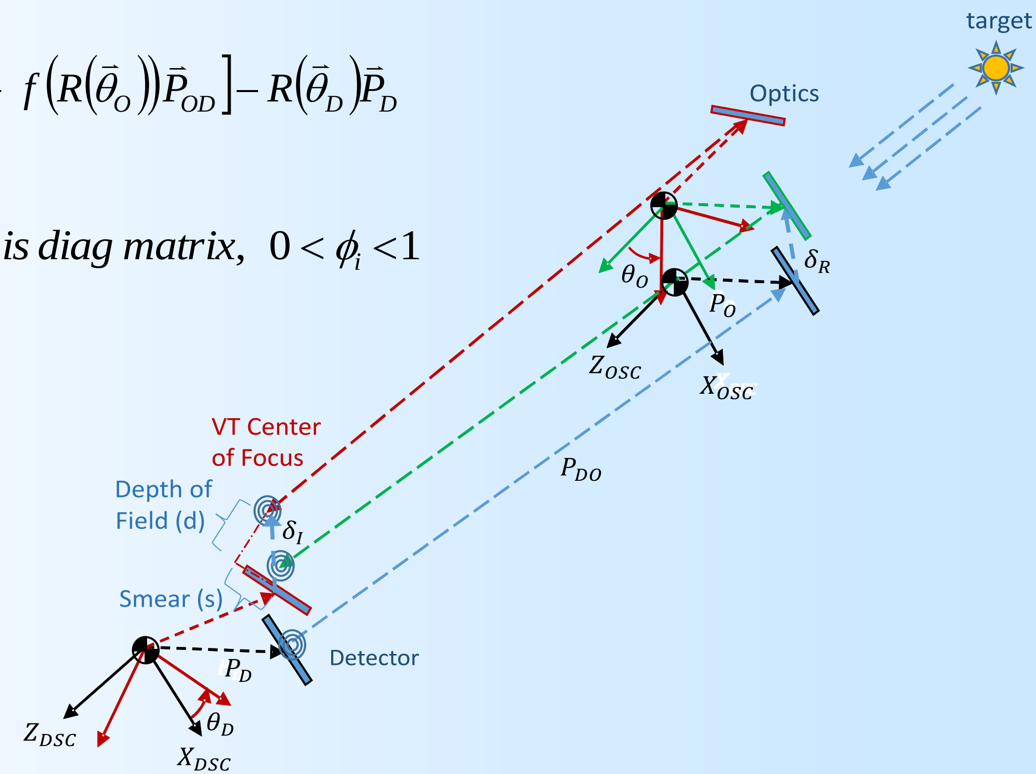
- **Science detector image smear and depth of field stability model**
  - **Considers detector and optics not co-located with S/C mass center**

$$\vec{\delta}_I = \begin{bmatrix} s_x \\ s_y \\ d \end{bmatrix} = \left[\vec{P}_D + \vec{P}_{DO} + \vec{\delta}_R - \vec{P}_O + R(\vec{\theta}_O)\vec{P}_O + f\left(R(\vec{\theta}_O)\right)\vec{P}_{OD}\right] - R(\vec{\theta}_D)\vec{P}_D$$

$$f\left(R(\vec{\theta}_O)\right) = [\, I + {}^n\tilde{\theta}_O \,], \quad {}^n\vec{\theta}_O = \Phi\vec{\theta}_O, \quad \Phi \; is\; diag\; matrix, \quad 0 < \phi_i < 1$$

$$\vec{\delta}_I = \begin{bmatrix} s_x \\ s_y \\ d \end{bmatrix} = \tilde{P}_D^x\,\vec{\theta}_D + \left[\Phi\tilde{P}_{DO}^x - \tilde{P}_O^x\right]\vec{\theta}_O + \vec{\delta}_R$$

$$\vec{\delta}_L = \begin{bmatrix} l_x \\ l_y \\ r_l \end{bmatrix} = \tilde{P}_L^x\,\vec{\theta}_D + \left[\Phi\,\tilde{P}_{LB}^x - \tilde{P}_B^x\right]\vec{\theta}_O + \vec{\delta}_R$$



  - **Same model is used for laser centration and ranging measurements**

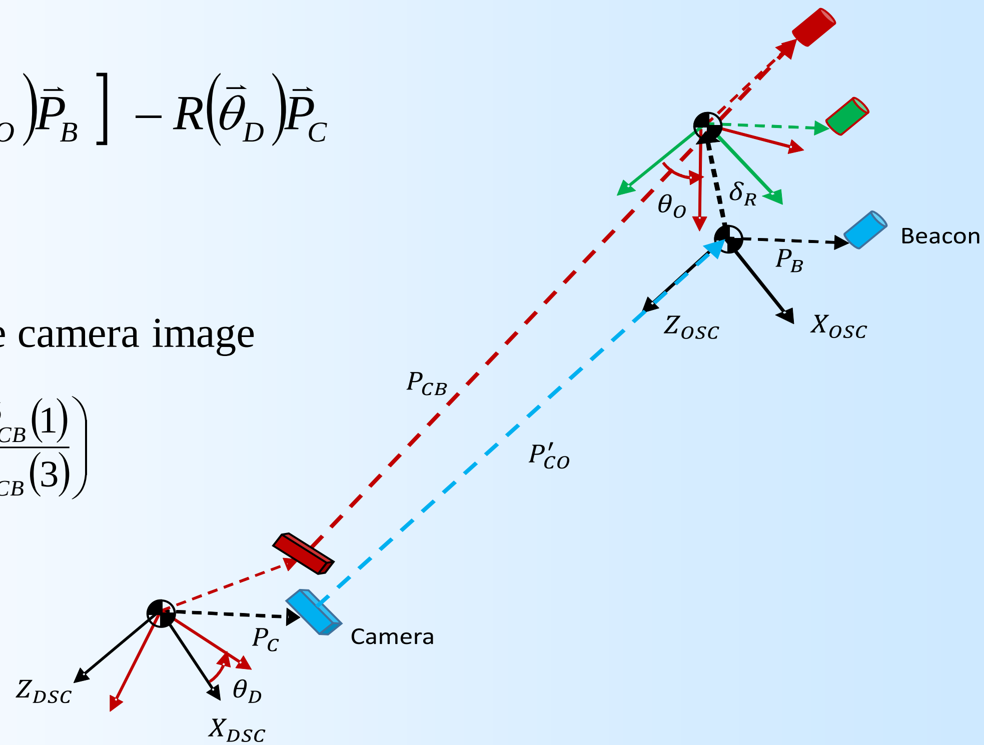
Alignment Camera Measurement Model

- **Measurement model for Alignment Camera (AC) to track laser beacon bearing angles.**
  - **AC used for acquisition of Laser Centration and Ranging elements.**

$$\vec{P}_{CB} = \left[\vec{P}_C + \vec{P}'_{CO} + \vec{\delta}_R + R(\vec{\theta}_O)\vec{P}_B\right] - R(\vec{\theta}_D)\vec{P}_C$$

Laser beacon centroids on the camera image

$$[\theta_x, \theta_y] = atan\left(\frac{\hat{P}_{CB}(2)}{\hat{P}_{CB}(3)}\right), atan\left(\frac{\hat{P}_{CB}(1)}{\hat{P}_{CB}(3)}\right)$$



VT Dynamics Framework for GN&C Design

- **Dual Spacecraft Relative Dynamics (Based on Luquette's work)**
  - **Restricted Three-body Framework**
  - **Mods: Additional gravitational bodies, and express equations in terms of Follower**

differential acceleration, expressed in an inertial frame,

$$\ddot{\bar{x}} = \ddot{\bar{r}}_F - \ddot{\bar{r}}_L$$

$$\ddot{\bar{r}}_F = -\sum_{i=1}^{n} \mu_i \frac{\bar{r}_{iF}}{\|\bar{r}_{iF}\|^3} + \bar{f}_{solar,F} + \bar{f}_{pert,F} + \bar{u}_{thrust,F}$$

$$\ddot{\bar{r}}_L = -\sum_{i=1}^{n} \mu_i \frac{\bar{r}_{iL}}{\|\bar{r}_{iL}\|^3} + \bar{f}_{solar,L} + \bar{f}_{pert,L} + \bar{u}_{thrust,L}$$

Can be simplified in terms of follower S/C, following derivation by Luquette.

- **Assume** $\|\bar{x}\| \ll \|\bar{r}_{iF}\|$, $\bar{x} = \bar{R}^{ref} + \bar{\delta}_R$ **and remove higher order terms.**

$$\ddot{\bar{\delta}}_R = \Gamma_{GG}\, \bar{\delta}_R + \Gamma_{GG} \bar{R}^{ref} + \bar{u}_R$$

$$\Gamma_{GG} = -\sum_{i=1}^{n} \frac{\mu_i}{\left\|\bar{r}_{iF}{}^{ref}\right\|^3} \left([I] - 3\hat{r}_{iF}{}^{ref} \left[\hat{r}_{iF}{}^{ref}\right]^T \right)$$

VT Dynamics Framework for GN&C Design

- **Inertial Measurement Sensor (Accelerometers)**

The acceleration, $\ddot{\bar{\delta}}_F{}^{m}$, at a specific sensor location, $\bar{r}_A$, can be represented as,

$$\ddot{\bar{\delta}}_F{}^{m} = \ddot{\bar{\delta}}_F + \bar{\omega}_F \times (\bar{\omega}_F \times \bar{r}_A) + \dot{\bar{\omega}}_F \times \bar{r}_A + \bar{b}_A + \bar{\nu}_A$$

Acceleration can be expressed in terms of forces / torques on S/C

$$\ddot{\bar{\delta}}_F = \bar{u}_{F_{T_0}} + \overline{\delta u}_{F_T} + \bar{u}_{F_E} \qquad \dot{\bar{\omega}}_F = I_F{}^{-1}\left(\bar{T}_{F_{T_0}} + \overline{\delta T}_{F_T} + \bar{T}_{F_E}\right)$$

And reduced to following linear form,

$$\ddot{\bar{\delta}}_F{}^{m} = \left([I] - r_A^x\, I_F{}^{-1} r_T^x\, m_F\right)\bar{u}_{F_{T_0}} + \left([I] - r_A^x\, I_F{}^{-1} r_T^x\, m_F\right)\overline{\delta u}_{F_T}$$
$$+ \left([I] - r_A^x\, I_F{}^{-1} r_E^x\, m_F\right)\bar{u}_{F_E} + \bar{b}_A + \bar{\nu}_A$$

- **Inertial Reference Unit (Accelerometers)**

$$\dot{\theta} = \bar{\omega}_F{}^{m} - \bar{b}_{\omega_F} + \bar{\nu}_{\omega_F}$$

Case Study: GN&C Design for Heliophysics Mission

Closed Loop GN&C Simulation Case Study – Photon Sieve

- GN&C design framework applied to an example problem to illustrate trades inherent in PFF for VT.
- Photon Sieve Optics (difractive optics, ~0.5 m aperture). Solar Imaging at milli-arc-sec level

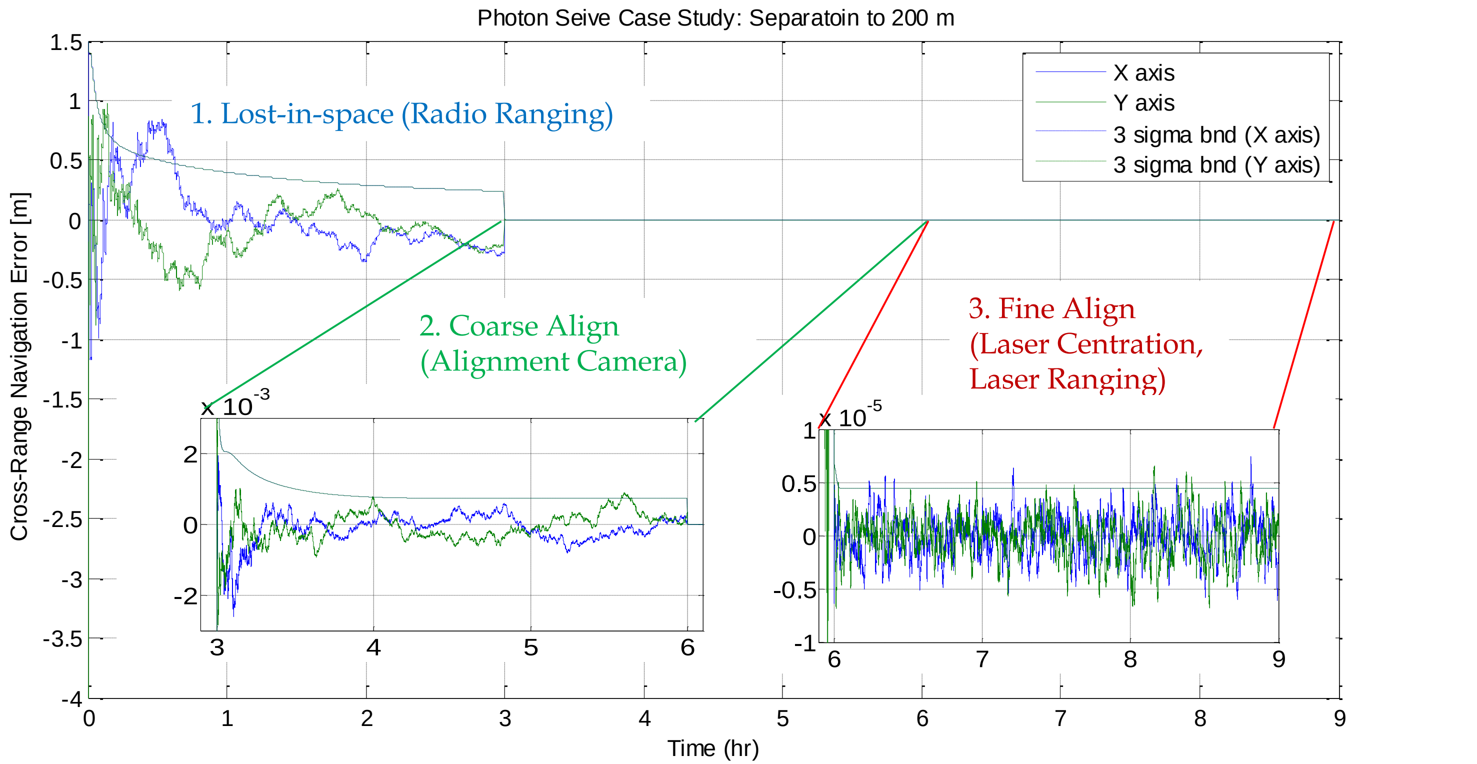
Table 1, Photon Sieve VT Alignment Requirements and Component Specifications

Parameter	Requirement (3s)		Component	Specification (3s)
Image Smear	6 microns		Laser Centration	30 microns
Depth of Field	1 mm		Laser Ranging	0.5 cm
S/C separation	200 m		Microthruster	5 mN-sec (min Impulse)
Pointing Stability (Optics S/C)	5 milli-arc sec (Sun) 10 arc-sec (roll)		Fine Sun Sensor	30 milli arc-sec
Pointing Stability (Detector S/C)	10 arc-sec		Star Tracker	6 arc-sec (transverse) 30 arc-sec (boresight)

- State estimation: Extended Kalman Filter, continuous state propagation, discrete measurements
  - Sequential Measurement updates to avoid numerical issues of large matrix inverses
- Separate PID Control for each of 9 DoF, (3) Relative translation, (3) Optics S/C Att, (3) Optics S/C Att
- All Measurement and Actuator models include random + systematic (1st order Markov) errors

Case Study: GN&C Design for Heliophysics Mission

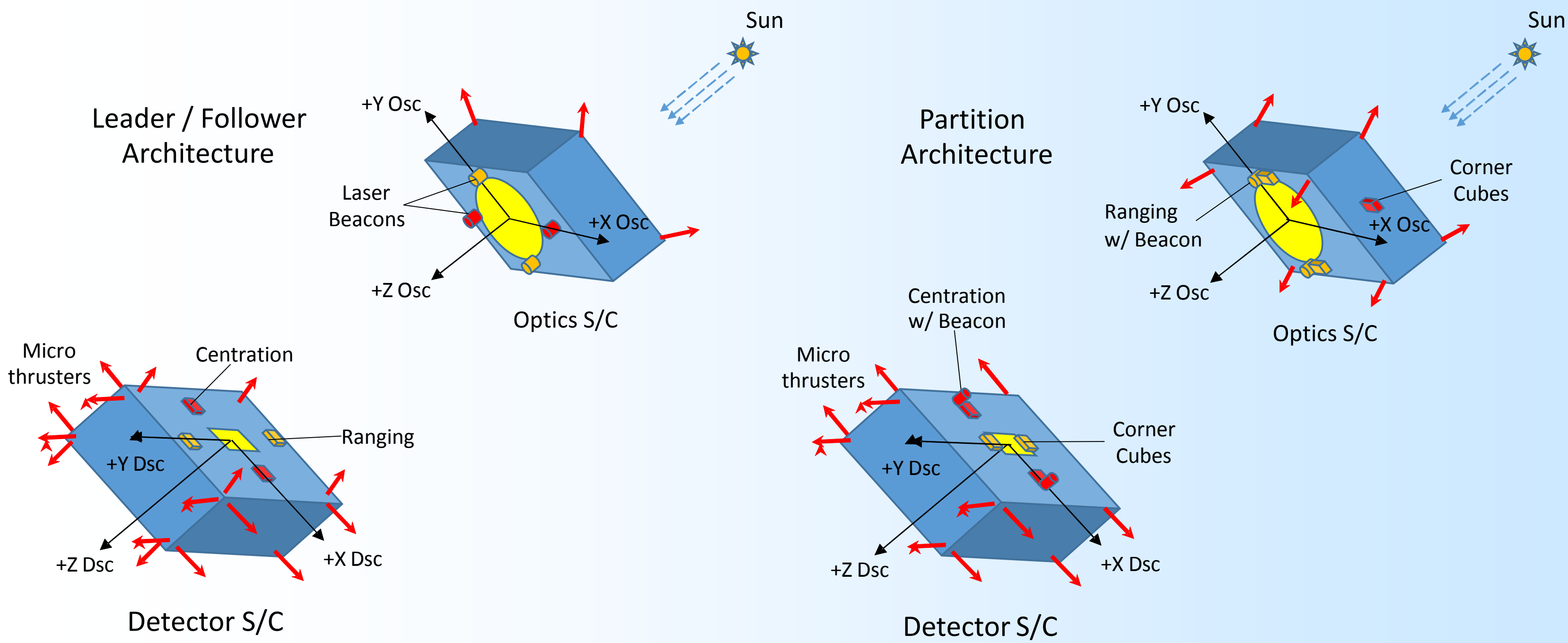
- **Simulation of Navigation modes (Leader/Follower) illustrates fine align acquisition**



1. **Lost-in-space: Radio Range (60 cm) , Radio bearing (9 deg)**
2. **Coarse Align: Alignment Camera (50 arc-sec), Star Tracker (ST) (6, 6, 30 arc-sec)**
3. **Fine Align: Laser Centration (30 μm), Laser Ranging: (1 cm), ST(6, 6, 30 arc-sec), Sun Sen (10e-3 arc-sec)**

Case Study: GN&C Design for Heliophysics Mission

- **Evaluation of Leader/Follower and Partition Architecture illustrates GN&C trades**



Leader/Follower architecture has two possible deficiencies

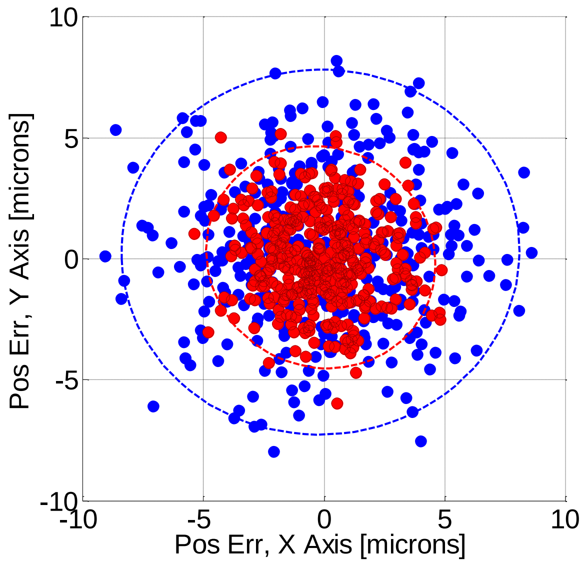
- **Comm link required to send Optics S/C Attitude to EKF on Detector S/C. Comm delay/timing sync**
- **Requires Full 6 DoF control on Detector S/C. Thruster coupling may result in poor performance**

Partition architecture: Control / Estimation is partitioned among the two S/C

- **Avoids multi-platform attitude coupling in the measurement process**

Case Study: GN&C Design for Heliophysics Mission

- **Evaluation of Leader/Follower and Partition Architecture illustrates GN&C trades**



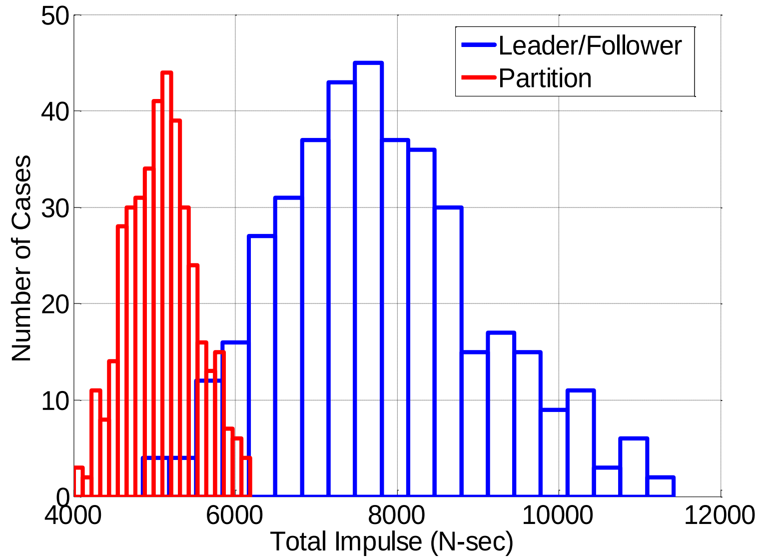


Figure 5 – Performance results of two representative GN&C architectures for the VT

- **Decoupling of laser centration/ranging measurements from the S/C attitude, (sensor positioning)**
  - **Improved transverse alignment observability / performance in the Partition architecture.**
- **Partition architecture performance meets Photon Sieve alignment requirements**
  - **~ 5x error reduction obtained from model-based estimation over laser centration measurements.**
  - **Total impulse for PFF (5 year) is reduced 35%. Solar pres along VT axis (Optics S/C is ½ mass of Detector S/C)**

Conclusions

- Developed General 9 DoF GN&C framework dual S/C PFF for application to VT missions
- GN&C performance assessment for a representative Heliophysics VT imaging mission concept illustrates the potential trade-offs inherent in the choice of system architecture for GN&C design and mission concept.

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